Evaluation of PENCRV3D for Determination of Ordnance Ground Penetration

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Abstract

An economical and accurate method of predicting the ground penetration depth of fired ordnance is needed to determine the required depth of excavation for unexploded ordnance (UXO) sites. PENCRV3D is a software program developed for predicting projectile penetration into curvilinear geologic/structural targets. The program was developed under the hardened structures research program at the U.S. Army Corps of Engineers Waterways Experiment Station. PENCRV3D predicts the ordnance trajectory through the soil target as well as other response characteristics such as the yaw, pitch, and roll angles and their respective rates of change in 3D space as a function of time. Particularly attractive is the fact that the model has been validated with field test data.

The mathematical model used four primary parameters which commonly have a wide range of possible values. These input parameters; projectile center of gravity, striking velocity, angle of fall, and target soil type, usually are not well defined and an engineering estimate must be used. Results showing the sensitivity of the model to this input are presented as well as a feasibility discussion as to the use of PENCRV3D as a solution to predicting UXO ground penetration.

Introduction

PENCRV3D is a three-dimensional (3D) projectile penetration code developed by the US Army Corps of Engineers Waterways Experiment Station (WES) [1]. PENCRV3D calculates the trajectory of a rigid, axisymmetric projectile upon its impact on, and penetration into, complex geological and structural targets. The program uses a differential area force law (DAFL) formulation to solve the six equations used in describing the 3D motion. The surface of the projectile is divided longitudinally and circumferentially into a finite number of generally rectangular elements. The stress normal to each element, representing the penetration resistance of the target, is calculated and applied to the center of each element at a series of discrete time steps. The total force is obtained by summing over all the elements, and is used to compute the trajectory and position of the projectile as it passes through the various target layers. The discretization of the projectile and the definition of the target are defined by the user. PENCRV3D also allows the definition of multiple target layers in the model definition. The target can be any combination of soil layers and structural elements that can be defined by a curvilinear function. With this method of analysis, PENCRV3D should yield very good results provided an acceptable tolerance in the accuracy of input data is achieved. Particularly attractive is the fact that the model has been validated with field testing.

PENCRV3D has been evaluated with respect to other methods of predicting the penetration of ordnance into the ground. When the input data is reasonably accurate, PENCRV3D predicts ground penetrations that reasonably match actual penetration depths. More information on this comparison can be found in the paper, "Estimating Ordnance Penetration into Earth" by Michelle M. Crull, in the proceedings of this conference.

Certain data, such as projectile center of gravity, striking velocity, etc., are difficult to precisely obtain for specific ordnance and at specific UXO remediation sites. The exact shape and center of gravity of the round must sometimes be determined from drawings of the round, and often detailed drawings are not available. The impact velocity and angle of fall (the angle between the axis of the round and the target at impact) are determined by the locations of firing points, firing angle, and propellant charges used, and these data are usually not known with certainty for any OE site. Specific soils conditions vary, and exact data on the soil types may not be available. Therefore, the use of numerical modeling techniques to predict the munition's depth of penetration into earth should be used with caution. Before using unknown or inaccurate input data, some insight is desired as what leverage this lack of accuracy has on the final results

After reviewing the PENCRV3D users guide, it was determined that the mathematical model used four primary parameters which commonly have a wide range of possible values. These input parameters; projectile center of gravity, striking velocity, angle of fall, and target soil type, are often not well defined and an engineering estimate must be used. The intent of this study was to examine the sensitivity of the model to this input and to estimate the time feasibility of PENCRV3D as a solution to predicting unexploded ordnance ground penetration.

Sensitivity Analysis

In order to evaluate the sensitivity of PENCRV3D, a baseline ordnance impact case was established. The case to be evaluated was the impact of a 155-mm M107 projectile onto a flat ground surface. The standard shape for the 155-mm round as defined in PENCRV3D was used. The striking velocity and angle were drawn from typical values in the firing tables for the 155-mm M107 [2]. The striking velocity was 705 ft/sec at a striking angle of 14 degrees from horizontal. The target used was a single layer of sand, defined by a soil index number of 8. In order to evaluate the sensitivity of the PENCRV3D model, the four primary parameters of interest were varied independently.

Sensitivity to Center of Gravity

Detailed geometric information of a selected ordnance frequently is not readily available. Therefore, estimates based on engineering judgment must be used to fill in the missing information relating to the makeup of a projectile. Although the center of gravity (COG) can be precisely determined once the missing information has been estimated, the end result obviously is still an estimate. In testing the model for sensitivity to this input, the COG was varied along the axis of a the 155-mm projectile about 1.7 inches, or about 9.3%, in both directions from its original location of 18.299 inches from the nose tip.

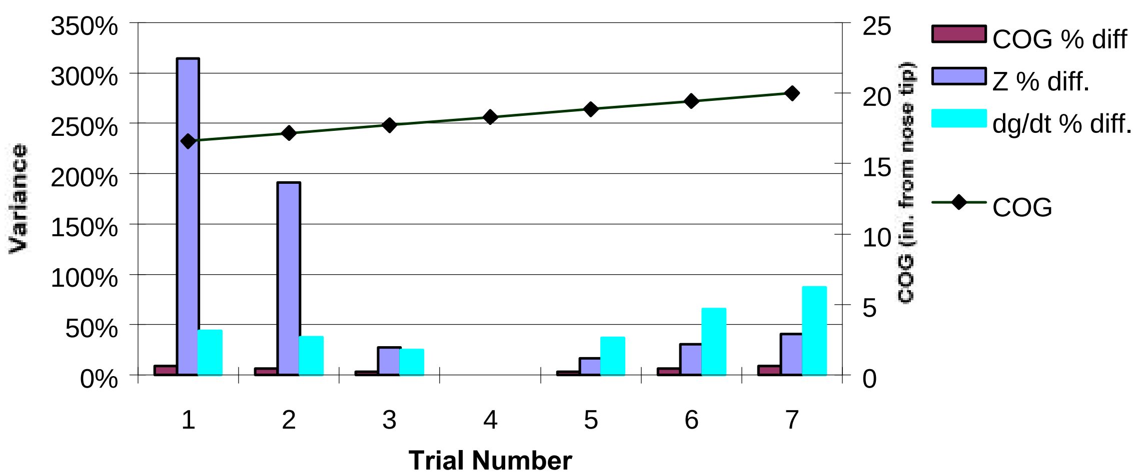
The results of the COG sensitivity test are shown in Table 2. This table lists the COG location, maximum penetration depth, final penetration depth, and percent variances from the baseline case (trial run 4). Negative penetration depths denote a position below the ground surface; positive penetration depths denote a position above the ground surface. The results are also shown graphically in Figure 1. This figure shows the results in terms of both maximum depth of penetration into the soil and pitch angle rate. The pitch angle rate is the rate at which the angle of the round from the horizontal changes over time. Therefore, it is a measure of how quickly the round is turning back toward the surface, or "porpoising".

The calculations showed a 314% increase in depth with a 9.3% decrease in COG position from the nose tip. Conversely, a 41% decrease in depth was observed with a 9.3% increase in the COG position from the nose tip. As shown, the maximum pitch angle rate varies from 44% to 87% as the COG varies 9.3% toward and away from the nose respectively. As expected, the model's sensitivity to the COG is analogous to the behavior of a common yard dart. That is, as the COG moves closer to the front of the projectile, the projectile will tend to go deeper into the target as well as decrease the pitch rate or "porpoising" effect. However, the degree of sensitivity is the focus of this analysis and is summarized in Figure 1.

Table 1. Results of PENCRV3D Sensitivity Test for Center of Gravity

trial #	COG (in. from nose tip)	Maximum Penetration Depth Z (in.)	Final Penetration Depth (in.)	Maximum Pitch Rate (rad/sec)	COG % Difference	Z % Difference	Max Pitch Rate % Difference
1	16.60	-8.37	-8.37	49.23	9.30%	314.44%	43.74%
2	17.17	-5.89	-5.89	54.75	6.20%	191.46%	37.43%
3	17.73	-2.57	1.14	65.60	3.10%	27.35%	25.03%
4	18.30	-2.02	6.83	87.50	0.00%	0.00%	0.00%
5	18.87	-1.68	9.59	120.00	3.10%	16.92%	37.14%
6	19.43	-1.40	10.73	144.86	6.20%	30.92%	65.55%
7	20.00	-1.19	11.35	163.94	9.30%	41.04%	87.36%

Figure 1. Results of PENCRV3D Model Sensitivity Test for Center of Gravity



As a supplementary exercise, a comparison was made between the COG used in sample problem 1 of the PENCRV3D users guide and that calculated through MicroStation CAD methods. Both projectiles were a 155-mm projectile. The geometry used in the MicroStation model was taken from a rough drawing of a M107 artillery shell. By estimating the gaps in the geometry definition on the drawing, the COG was calculated from a 3D CAD model of the M107.

As seen in Table 2, this procedure showed a COG distance of 18.235 in. from the nose tip as opposed to 18.299 in. distance in the example problem (a 0.3% discrepancy). This exercise showed that a reasonably accurate COG could be obtained by building a 3D model of the projectile.

Table 2. 155-mm M107 COG Calculation from MicroStation

	M	xi	M * xi
Casing	80.115	18.872	1511.898
Filler	14.599	16.239	237.065
Fuse	1.510	3.777	5.703
Totals	96.224		1754.666

$$\frac{S\ Mxi}{S\ M} = \frac{1754.666}{96.224} = 18.235 \text{ in}$$

Sensitivity to Angle of Fall and Striking Velocity

In testing the model for sensitivity to the angle of fall, or striking angle, the pitch angle (γ) of the round was varied 1^o, or 7.14%, in both directions from the original angle of 14^o from the horizontal. The results of the PENCRV3D calculations are listed in Table 3. As expected, the PENCRV3D model showed a high degree of sensitivity to the pitch angle. Varying the pitch angle by 7.14% in each direction showed an 83% increase and 47% decrease in depth of penetration. The pitch rate was somewhat less sensitive to the pitch angle, but still showed a 27% change in both directions. The degree of sensitivity is summarized in Figure 2.

The sensitivity of the model to the striking velocity is shown in Table 4 and Figure 3. The velocity was varied in increments of 50 ft/s for a total of a 150 ft/s (21%) increase and decrease from the original 705 ft/s. The results showed that by increasing and decreasing the velocity by 21%, the maximum depth of penetration was increased by 111% and decreased by 70%, respectively. The max pitch rate varied in relatively close proportion with the velocity.

Table 3. Results of PENCRV3D Sensitivity Test for Striking Angle

trial #	Pitch Angle γ (deg.)	Maximum Penetration Depth Z (in.)	Final Penetration Depth (in.)	Max Pitch Rate $d\gamma/dt$ (rad/sec)	γ % Difference	Z % Difference	Max Pitch Rate ($d\gamma/dt$) % Difference
1	15.0	-3.69	-3.69	63.86	7.14%	82.77%	27.01%
2	14.5	-2.77	3.16	68.71	3.57%	36.84%	21.48%
3	14.3	-2.37	4.61	76.34	1.79%	17.14%	12.75%
4	14.0	-2.02	6.83	87.50	0.00%	0.00%	0.00%
5	13.8	-1.75	8.09	95.33	1.79%	13.24%	8.95%
6	13.5	-1.50	9.25	102.40	3.57%	25.57%	17.03%
7	13.0	-1.07	10.63	111.05	7.14%	47.00%	26.91%

Figure 2. Results of PENCRV3D Sensitivity Test for Angle of Entry

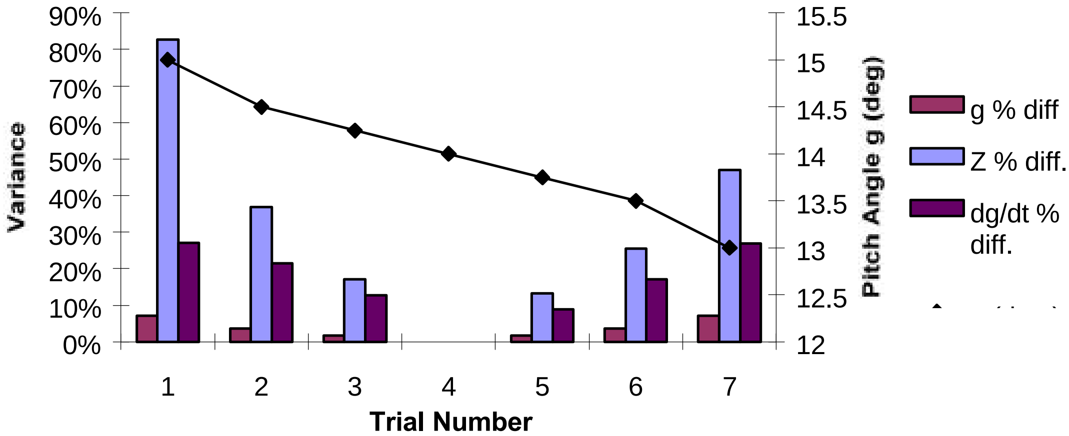
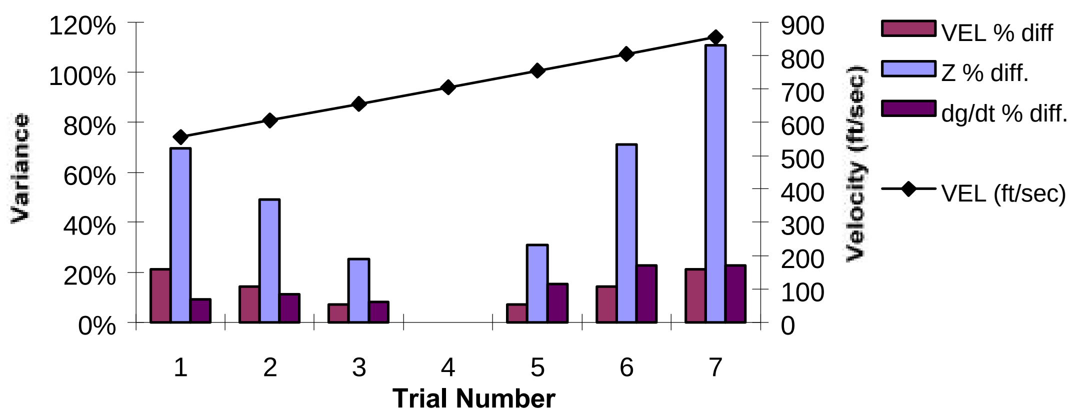


Table 4. Results of PENCRV3D Sensitivity Test for Striking Velocity

trial #	Striking Velocity (ft/sec)	Maximum Penetration Depth Z (in.)	Final Penetration Depth (in.)	Max Pitch Rate $d\gamma/dt$ (rad/sec)	Striking Velocity % Difference	Z % Difference	Max Pitch Rate ($d\gamma/dt$) % Difference
1	555	-0.61	14.01	95.61	21.28%	69.71%	9.27%
2	605	-1.03	12.44	97.37	14.18%	49.03%	11.28%
3	655	-1.51	9.96	94.53	7.09%	25.32%	8.04%
4	705	-2.02	6.83	87.50	0.00%	0.00%	0.00%
5	755	-2.65	4.15	74.12	7.09%	31.10%	15.29%
6	805	-3.46	-2.22	67.54	14.18%	71.09%	22.81%
7	855	-4.26	-3.98	67.48	21.28%	110.78%	22.88%

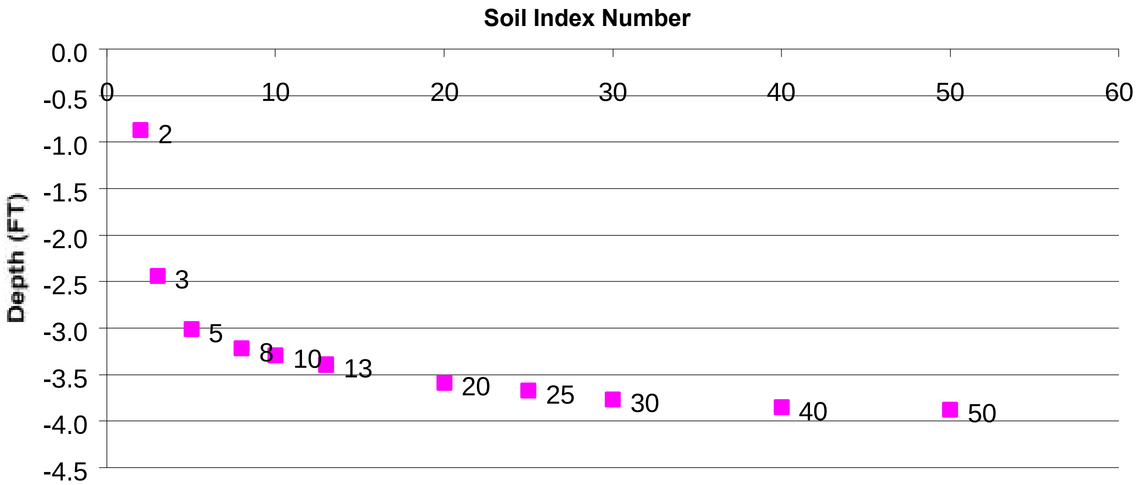
Figure 3. Results of PENCRV3D Model Sensitivity Test for Entrance Velocity



Sensitivity to Soil Type

Another input parameter that is usually not well defined is the material properties of the target. This is especially true in the case of a soil target. PENCRV3D defines the soil properties in terms of a soil index number. Values of soil index number in the PENCRV3D database of soil range from 2 to 50. The definitions range from well-cemented sand on the low end to wet clay on the high end. The objective of this test was to see how the depth of penetration was affected by varying only the soil type. The velocity and angle of fall was chosen from FT 155-AS-1 firing tables based on the size of the round and striking velocity. As a worst case, a 30^{o} angle of fall was used with a 705 ft/s entry velocity. The range of soil type with the highest rate of change is between 2 and 20, as shown in Figure 4. The depth is not significantly affected in the range from 21 to 50.

Figure 4. Maximum Depth of Penetration as a Function of Soil Index



Discussion

The purpose of this test was not to predict the general behavior of the ordnance trajectory in the target material but to examine the sensitivity of the PENCRV3D model to certain parameters. The sensitivity analysis shows that the COG needs to be within a 98% confidence level to yield penetration depths accurate to within 20%. It should be noted that this conclusion results from a 14^{o} angle of fall and a soil index number of 8. The interaction of these variables was not tested. The analysis also shows that the pitch angle input parameter needs to be at a 98% confidence level to obtain depth results to within 20% accuracy. Again, lack of interaction testing should be noted. The entry velocity parameter was somewhat more forgiving with a 6% change in velocity resulting in a 20-25% variance in penetration depth.

One important result to note is that the final penetration depth is also quite sensitive to the vaiation of COG, striking angle and striking velocity. The results in Tables 1, 3 and 4 above show this sensitivity. For relatively small variations in each of these parameters, the basic prediction of whether the round stops beneath the surface (a negative final depth) or above the ground (a positive final depth) can change. Therefore, for rather small errors in the input data, the PENCRV3D model may predict that the round exits the ground, and that there should be no subsurface rounds, when in fact there may indeed be rounds beneath the ground.

Conclusion

Upon presentation of this study's results, it is hoped that the reader will gain some insight as to the acceptable tolerance of the input parameters when using numerical models as well as the level of effort needed to complete such an analysis. The use of PENCRV3D as a numerical modeling tool would be a possible solution for determining UXO penetration depth. From reviewing the users guide and performing the sensitivity analysis, it is estimated that approximately one man-week of effort would be required to provide penetration results back to the field. The majority of this time would be spent on archive searches for input data, such as that previously discussed, so that results could be given within an acceptable tolerance. A PENCRV3D analysis would be more accurate than in-house spreadsheet calculations but at the expense of more time. Alternatively, hydrocode analysis would be the most accurate in theory because of the energy principles used in the solution. However, an additional feasibility study is needed to determine the cost associated with this type of analysis. In general, a low cost estimate of UXO ground penetration can be accomplished with spreadsheet calculations. PENCRV3D lends itself well to a more detailed calculation that is more costly. If a precise depth of penetration is the goal, hydrocode analysis is a more likely solution, but at the highest cost.

References

1. Adley, M. D., et. al., "Three-Dimensional Projectile Penetration Into Curvilinear Geologic/Structural Targets: User's Guide for PENCRV3D", Instruction Report SL-97-1, U.S. Army Corps of Engineers Waterways Experiment Station, Vcksburg, MS, January 1997.

2. FT 155-AS-1, Firing Tables for Cannon, 155mm Howitzer, Headquarters, Department of the Army, 31 December 1990.